भारतीय मानक

Indian Standard

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प्राकृतिक झीलों में तलछट का मापन और नियंत्रण करना — दिशानिर्देश

Measurement and Control of Sediments in Natural Lakes — Guidelines

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FOREWORD

This Indian Standard was adopted by the Bureau of Indian Standards, after the draft finalized by the Reservoirs and Lakes Sectional Committee had been approved by the Water Resources Division Council.

Lakes receive a wide assortment of suspended materials from rivers, precipitation, catchment erosion, shoreline erosion, pollution sources and biological activities. These materials are referred to as sediments and are a very important factor in the life of a lake.

Sedimentation is one of the serious problems of many lakes causing reduction in lake capacity and useful life of the lake. Sedimentation seriously affects the ecological behaviour of lakes and determines to a large extent; the water quality of lakes. The interaction of sediments with the lake water, both within the water column and at the bed of the lakes, controls the quality of the lake water. The chemical and biological activities of sediments produce heat, contributing to the heat budget of the lake. Sediments also determine the biological productivity of lakes. Although high concentration of suspended matter may result in low primary production because of restricted light penetration, supply of excess nutrients to lake through sediments increases its productivity. Sediments also contain biological life as they act as substrate for bacterial activity. The availability of dissolved oxygen in lakes may be limited due to high sediment oxygen demand by the bacterial activity. Sediments can destroy the fish when soil particles contain contaminants such as pesticides and toxic material. Excessive sediments can result in reduction in the diversity and abundance of aquatic life. Diversity and population size of fish species, mussels and benthic (bottom-dwelling) macro-invertebrates associated with coarse substrates can be greatly reduced if the substrates are covered with sand and silt. Sedimentary processes may also cause changes in the lake basin forms. Benthos and fish are affected not only by the suspended sediments but also by the modification of habitat caused by depositional sediments. As such, it is essential to control and manage the lake sedimentation.

The composition of the Committee responsible for the formulation of this standard is given in Annex A.

For the purpose of deciding whether a particular requirement of this standard is complied with the final value, observed or calculated, expressing the result of a test or analysis, shall be rounded off in accordance with IS 2 : 2022 ‘Rules for rounding off numerical values (*second revision*)’. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

Indian Standard

MEASUREMENT AND CONTROL OF SEDIMENTS IN NATURAL LAKES — GUIDELINES

1 SCOPE

This standard lays down guidelines for measurement and control of sedimentation in natural lakes.

2 REFERENCES

The standards given below contains provisions which, through reference in this text, constitute provisions of this standard. At the time of publication, the editions indicated were valid. All standards are subject to revision and parties to agreements based on this standard are encouraged to investigate the possibility of applying the most recent editions of the standards given below:

IS No.	*Title*
IS 6339 : 2013	Hydrometry — Sediment in streams and canals — Determination of concentration, particle size distribution and relative density (*first revision*)
IS 13665 : 2017/ ISO 6421 : 2012	Hydrometry — Methods for assessment of reservoir sedimentation (*first revision*)

3 TERMINOLOGY

For the purpose of this standard, the following definitions shall apply.

3.1 Artificial Lakes or Reservoirs — Artificial Lakes or reservoirs can be defined as man-made lakes constructed by damming a river valley or by artificial excavation.

3.2 Natural Lake or Lake — A natural lake is an inland basin filled with water. It is formed because of some geological process like water fills any natural depression and they have a natural shoreline along its periphery. Because of the continuous action of the waves, this shoreline is generally barren.

3.2.1 On the basis of their origin; lakes are divided into a number of categories and sub-categories. Some of the important classes are: tectonic lakes, volcanic lakes, glacial lakes, solution lakes; lakes formed by stream action, lakes formed by wind action, lakes formed by shoreline processes, lakes produced by landslides, lakes formed by organic accumulation, lakes formed by activity of higher organisms and lakes formed by impact of meteorites. Lakes whose origin is not known or cannot be covered under any of these categories are clubbed as lakes of unknown origin.

3.2.2 On the basis of their thermal behaviour such as stratification, mixing and number of overturns per year, lakes are mainly classified as:

3.2.2.1 *Amictic lakes* — These lakes are completely insulated from outside influences of water and other factors because of the permanent ice cover. There is no mixing of water.

3.2.2.2 *Holomictic lakes* — These lakes are wholly mixed that is circulation is complete and extends up to bottom.

NOTE — Holomictic lakes are further classified as dimictic lakes and monomictic lakes. Dimictic lakes undergo two overturns per year. In monomictic lakes, there is only one overturn per year. Monomictic lakes may be either cold monomictic (overturn in summer) or warm monomictic (overturn in winter).

3.2.2.3 *Meromictic lakes* — These lakes are permanently stratified. They do not circulate completely throughout the year as stratified bottom never circulates.

3.2.3 Trophic status describes the productivity status of lakes based on nutrient concentrations, algal population etc. Based on the trophic status, three major categories of lakes are identified.

3.2.3.1 *Oligotrophic lakes* — Lakes with lowest trophic level, low level of nutrients and clean water.

3.2.3.2 *Mesotrophic lakes* — Lakes with intermediate properties between those of oligotrophic to eutrophic lakes.

3.2.3.3 *Eutrophic lakes* — Lakes with highest trophic level and high concentration of nutrients and plankton; water is murky.

3.2.4 Based on the chemical nature of the lake water and calcium content, lakes have been variously classified.

3.2.4.1 Based on the chemical nature of the lake water, lakes can be acid lakes, saline lakes or fresh water lakes.

3.2.4.2 Based on the calcium carbonate contents, lakes are classified as soft water lakes, medium water lakes, hard water lakes and very hard water lakes.

3.2.5 Based on the presence of outlets, lakes are classified as open lakes and closed lakes.

3.2.5.1 *Open lakes* — These lakes are also called exorheric lakes. These are those lakes that have some form of outlet.

3.2.5.2 *Closed lakes* — These lakes are also called endorheric lakes. They do not have any outlets. They lose water only by evaporation and do not have any significant seepage loss.

3.2.6 Based on the nature of inflow, a lake can be classified as seepage lake or drainage lake.

3.2.6.1 *Seepage lake* — A seepage lake is one which do not have any stream draining into it. Seepage lakes are recharged by ground water only.

3.2.6.2 *Drainage lakes* — These lakes have surface water as the main input.

3.3 Bed Load — Sediments that are in almost continuous contact with the lake bed, while carried by rolling, sliding or hopping along the bed of the lake (*see* IS 6339).

4 GENERAL

4.1 Difference Between a Natural Lake or Lake and an Artificial Lake or Reservoir

Natural lakes are formed because of some geological process, as water fills any natural depression, and they have a natural shoreline along their periphery. The reservoirs and tanks, on the other hand are artificially created, the reservoir is created by damming a river valley and the tanks are created by artificial excavation.

There are other technical differences also. Output from the lakes is near the surface whereas outlet of a reservoir is at one of the several depths. Lower most depression in a lake can occur anywhere in its basin but the maximum depth of the reservoir is always near the dam. A reservoir bottom has a regular slope from head to tail, while in natural lakes the bottom slopes is not uniform. Reservoirs also have greater areal water load and shorter residence time than lakes. Fig. 1 shows a typical cross section of natural lakes and reservoirs.

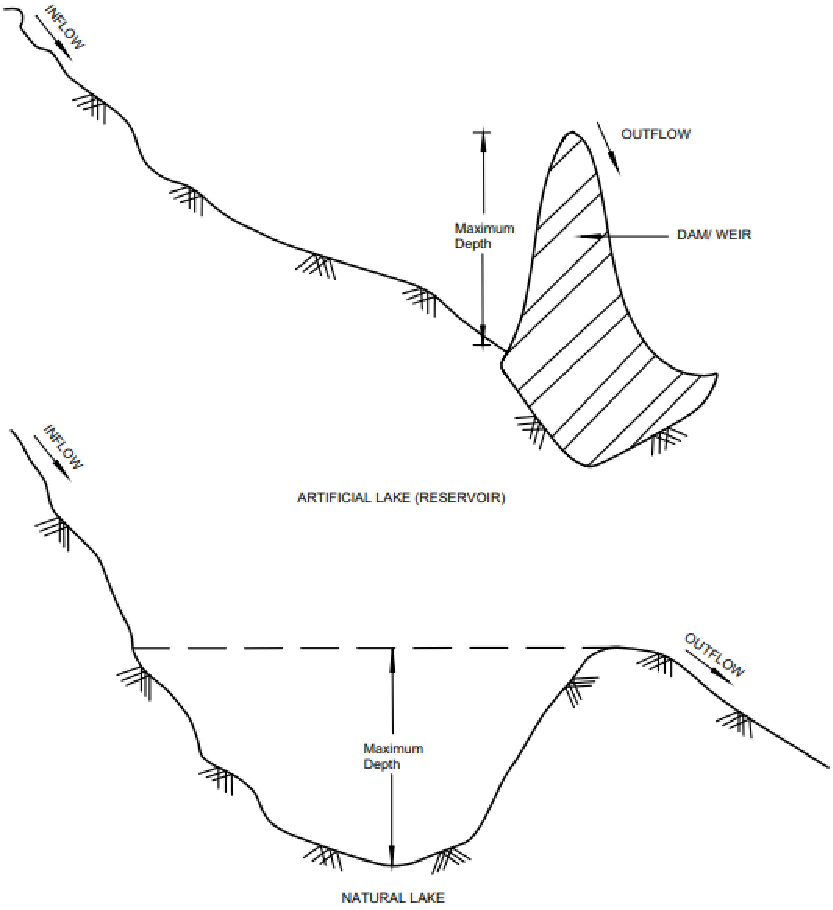

FIG. 1 TYPICAL CROSS-SECTION OF NATURAL LAKE AND ARTIFICIAL LAKE

4.2 Lake Sedimentation Process

4.2.1 Lake sediments are comprised mainly of clastic material (sediment of clay, silt and sand sizes), organic debris, chemical precipitates, or combinations of these. The relative abundance of each depends upon the nature of the local drainage basin, the climate and the relative age of a lake. The sediments of a lake in a glaciated basin, for example, will first receive coarse clastics, then finer clastics, chemical precipitates and then increasingly large amounts of biological material, including peats and sedges.

4.2.2 Lake sediments are an important and integral part of the lake ecosystem. They reflect changes in land-use, and lake characteristics, and are often regarded as an historical archive. They also affect the present structure and function of lake ecosystems. Suspended particulate matter (SPM) in lakes mainly emanate from tributaries (allochthonous matter), from living and dead matter produced in the lake (autochthonous matter), or from re-suspended materials. SPM regulates the transport of all types of water pollutants in dissolved and particulate phases; it regulates water clarity and the depth of the photic zone.

4.2.3 Sedimentation is the flux from water to sediments. Re-suspension is the advective flux from sediments back to water. Diffusion is the flux from sediments back to water, triggered by concentration gradients.

4.2.4 Lake sedimentation is the process in which particulate matter carried from its point of origin, by either natural or human-enhanced processes; is deposited in the lake. Nature of sediments coming to a lake depends upon the rock type in the drainage basin. Sedimentation rate for a lake is mainly dependent upon conditions in the drainage area like morphology, climate and land use. Deposition pattern depends upon morphological and hydrodynamic factors related to the water body. Water and wind are the main natural agents which bring sediments into the lake. Organic matter produced in the lake is an internal source.

4.2.5 The bed load brought by the river/stream/overland flow is initially deposited preferably on shallow water near the shores. Fine particles have low settling velocities and are kept in suspension by the water motion. Besides, there are also sediments that are re-suspended from the bottom, due to the influence of waves and currents. When the energy level is reduced due to decrease in the wind speed, then the sediments will settle to the bottom. Generally, they gather in the deeper areas. Consequently, the near shore areas will generally be void of fine sediments. Thus, the total sediment discharge includes the suspended-sediment discharge and the bed load discharge.

4.3 Lake Bottoms Based on Sedimentation

4.3.1 A proper understanding of the bottom dynamic conditions (erosion, transportation and accumulation) in lakes is essential in most sedimentological contexts. Fine cohesive materials generally dominate the open water areas, whereas coarser deposits (sand and gravel) dominate shallow regions where erosion and transportation of fine materials prevail. There is no physical model available which describes the linkage between the energy content of the water-mass and the capacity for sediment entrainment in open water areas. Water-mass energy generally depends on wind direction, duration, velocity, fetch and the presence of a thermo-cline etc. Entrainment depends on density, compaction, water, organic content of the sediments and the number and type of bottom fauna etc.

4.3.2 Four different methods are used to determine bottom dynamics, two are site specific and two other are lake specific. Site and lake specific methods each include one method based on collected field data, and one based on theoretical data. The cone apparatus is used to collect field data. It consists of two cones, one of which one has a narrow angle and the other has a wide angle, which are adjusted at zero at the sediment surface before releasing to penetrate the sediments. The differential cone penetration, referred as the penetration ratio, is used to indicate the degree of surficial sediment compaction. This instrument provides quantitative data on physical sediment characteristics which may be related to bottom dynamic conditions.

4.3.3 The shallow bottoms from which fine loose material is stirred up at every storm and where there are no extended periods of deposition are called erosion bottoms. Transportation bottoms prevail where fine material is deposited but where erosion takes place only during severe storms. Areas where fine material is deposited and erosion never occurs are called accumulation bottom. In shallow lakes there are no accumulation bottoms where material can deposit. The bottom sediments close to the shores as well as in the central parts of such lakes are a mixture of fine and coarse material.

5 METHODS FOR MEASUREMENT OF SEDIMENTATION

5.1 Sediments play an important role in elemental cycling in the aquatic environment. For the purposes of aquatic monitoring, sediment can be classified as deposited or suspended. Deposited sediment is that which found on the bed of a river or lake. Suspended sediment is found in the water column from where it is being transported by water movements. Suspended sediment is also referred to as suspended matter, particulate matter or suspended solids. Generally, the term suspended solids refers to mineral plus organic solids, whereas suspended sediment should be restricted to the mineral fraction of the suspended solids load.

5.2 Theoretically, both of the suspended-sediment discharge and the bed load discharge can be determined either by measuring the weight of sediment that passes a section in a given time or by combining the concentration, the area of flow and the velocity of the particles. However, in practice, the suspended sediment discharge is usually computed by the concentration method and the bed load discharge is usually computed by the weight method. Different methods are advised because suspended-sediment particles are transported for sustained periods of time at about the same velocity as that of the flow and bed load particles are usually transported intermittently at velocities less than that of the flow. Thus, suspended-sediment discharge can be computed from a concentration and a water discharge (the product of particle velocity and area of flow equals water discharge), whereas the bed load cannot.

5.3 Measurement of Bed Load

a) The simplest way to estimate bed load is to dig a hole in the stream bed, called bed load trap, just before it enters the lake, then remove and weigh the material that drops into it;

b) Bed load is also measured with bed load samplers which are lowered to the stream bed for a measured time, then brought up for weighing the catch. However, bed load samplers disturb the flow and changes the hydraulic conditions at the entry into the sampler. To remain stable on the bed it has to be heavy and the resting bed surface has to be a reasonably smooth bed;

c) Some of the popular bed load samplers in use are box or basket type sampler, pan or tray sampler, pressure difference samplers (for example, Arnhem sampler or Helley-Smith bed sampler), slot or pit samplers, pumping sampler, magnetic sampler, suction type sampler etc;

d) The bed load samplers are to be placed near the mouth of the lake where the in flowing stream discharges into the lake;

e) The number of sampling stations depends upon the width of the lake mouth (or stream). At least 20 equally spaced, transverse sampling stations are necessary to ensure that zones of both maximum and minimum transport are adequately sampled. The distance between two successive sampling stations should not be more than 15 m and less than 0.5 m;

f) Generally, two transverse surveys are adequate. Time for sampling at each section should be about 60 s; and

g) The mean bed load is estimated by taking average of bed load of the various transverse sections.

5.3.1 *Empirical Estimations*

The difficulty of obtaining reliable measurements of bed load has led to some attempts to calculate it from more easily measured parameters but these are not widely used. A very simple method based on knowing the suspended sediment concentration and the texture of both suspended material and bed material is given in Table 1. For Lakes situated in hilly region, concentration of rolling material may be calculated as

$$Y = 0.299\, X^{1.125}$$

where

Y = corresponding rolling material (in PPM); and

X = average sediment in suspension (in PPM).

Table 1 Maddock's Classification for Estimation of the Bedload

(*Clause* 5.3.1)

Sl No.	Suspended Sediment Concentration Parts Per Million	River Bed Material	Suspended Elements Texture	Bedload Discharge Expressed as % of Suspended Sediment Discharge
(1)	(2)	(3)	(4)	(5)
i)	Less than 1 000	Sand	Similar to the river bed	25 to 150
ii)	Less than 1 000	Gravel, rocks and hard clay	Low sand content	5 to 12
iii)	1 000 to 7 500	Sand	Similar to the river bed	10 to 35
iv)	1 000 to 7 500	Gravel, rocks and hard clay	25 % sand or less	5 to 12
v)	More than 7 500	Sand	Similar to the river bed	5 to 15
vi)	More than 7 500	Gravel, rocks and hard clay	25 % sand or less	2 to 8

5.4 Measurement of Suspended Load

a) Sample of suspended sediment can be collected by dipping a bottle, bucket or other container into the stream (called grab sampler), preferably at a point where it will be well mixed, such as downstream from a weir or rock bar. The sediment contained in a measured volume of water is filtered, dried and weighed. This gives a measure of the concentration of sediment and when combined with the rate of flow, gives the rate of sediment discharge;

b) If a single sample taken at any chosen depth, half the depth of flow is recommended for giving the best estimate of average sediment concentration;

c) Where the sampling consists of samples on vertical sections at several points across the stream, the recommended pattern is to use six equally spaced sections;

d) Various samplers which are in use includes depth integrating samplers, point integrating samplers, pumping samplers and automatic samplers;

e) Depth integrating sampler gives a single sample combined from small sub-samples taken from different points;

f) The point-integrating sampler remains at a fixed point in the inflowing stream and samples continuously during the time it takes for the bottle to fill. Opening and closing of valves of the sampler are controlled from the surface either electrically or by cables;

g) An automatic pumping sampler can be programmed to take series of samples as required on a rising and falling flood to cope with rising and falling rates of flow and the variations of sediment concentration at different flow rates. They can pump a small sample into a series of bottles, either at predetermined times and intervals, or as triggered by predetermined flow conditions, usually depth;

h) If it is required to take a series of samples as the river rises, then an array of automatic samplers can be set up in a vertical arrangement; and

j) For continuous measurement of suspended sediment concentration, optical turbidity meter can be used.

5.5 Measurement of Total Sediment Load

Separate measurements of suspended load and bed load may be necessary only for detailed experimental investigations or modeling studies. However, for most of the practical purposes, separate measurements are not necessary. A method of avoiding separate estimates of suspended load and bed load is to mix up all the moving sediments and then take a single sample of the mixture. Such a sample can be taken using a slot sampler at the turbulence flume. The other method is estimation of the deposited sediments in the lake.

5.6 Estimation of the Total Sediments Deposited in the Lake

The two important traditional methods are stream flow analysis and capacity survey.

5.6.1 *Stream Flow Analysis Method*

The method is the same for natural lakes and reservoirs. Description of the method is specified in IS 13665.

5.6.2 *Capacity Survey Method*

Under this category there are two methods:

a) Range line method or cross-sectional area method; and

b) Contour survey method.

In most surveys, a combination of both the methods is used. Both these methods are the same for natural lakes and reservoirs. Description of the methods is specified in IS 13665.

It is important that the procedures and techniques used in each capacity survey be accurately described and documented so that later surveys can be carried out in a similar manner and provides comparable data.

5.7 Other Methods of Estimation

5.7.1 *Radio Dating Technique*

For lakes where no previous sediment surveys exist, the radio dating techniques may be used. Two environmental isotopes namely ^{210}Pb and ^{137}Cs are mostly used for the purpose. ^{210}Pb method provides estimates of sedimentation rates for the last 100 to 150 years while ^{137}Cs gives estimates for the post 1954 period.

5.7.1.1 *^{137}Cs Method*

A mean sediment accumulation rate since 1954 or 1963 can be inferred from the age of the dated horizon and the thickness of sediment above it. The rates of sedimentation can be calculated from the depths of two principal time horizons that is 1954 and 1964, in the ^{137}Cs concentration profile. This is suitable for recent sediments only (last 60 to 70 years).

5.7.1.2 *^{210}Pb method*

This method is widely used to characterize sediments on relatively short time scale (< 150 years). The dating method is based on the release of ^{222}Rn gas (daughter of the ^{226}Ra) from the soil to the atmosphere. The short-lived ^{222}Rn (half-life 3.82 days) decays to ^{210}Pb, that returns to earth surface or water reservoir within weeks as a solid fallout. The ^{210}Pb activity is divided into two parts, the supported ^{210}Pb produced in-situ by the natural decay of ^{226}Ra, and the unsupported ^{210}Pb coming from the atmospheric fallout. The age of the sediment layer can be determined by means of the unsupported part. The method is reliable, particularly in stable environments with uniform sediment accumulation rates.

5.7.2 *Remote Sensing Techniques*

Aerial photographs or satellite images are used to trace turbidity plumes, which may help in defining the distribution of sedimentation.

5.7.3 *Laser Hydrography*

This is a comparatively new technique, which uses the airborne laser hydrographic technique wherein an aircraft mounted pulsed laser system collects a swath of discrete soundings along each flight line. It measures water depth exactly like a sonar using light instead of sound. It is suitable for large lakes.

6 SEDIMENTATION RATE

6.1 Estimation of Lake Sedimentation Volume (LSV)

The amount of sedimentation in a lake is usually described as sediment volume deposited in the lake. The volume of sediment accumulation in a reservoir is determined as the loss in water storage capacity of the lake over a period of time. The volume of sediment will then be the difference between the original volume of the lake (or volume at the time of previous survey) and the volume of the lake at the time it is surveyed again.

6.2 Rate of Sedimentation

6.2.1 The annual rate of sedimentation (R_s) is given as:

$$R_s = \frac{\Delta S}{\Delta t} \qquad \frac{m^3}{yr} \; or \; \frac{Ha.m}{yr}$$

where

ΔS = difference in storage capacity of the lake during the two surveys (in Mm^2.cm or $Ha.m$ and 1 m$^3 = 1\ Ha.m$); and

Δt = time lapse between the two surveys, (in year).

Alternatively, amount of lake sediment may also be described as sediment mass as measured by the sediment tonnage. It is a measurement which is not dependent on the degree of compaction and is therefore, a parameter that can be used to assess the relative sediment accumulation in lakes. However, the weight of sediment in a lake indicates the rate of sediment inflow from the lake catchment and therefore, provides an estimate of the rate of erosion of the catchment soils.

If the sedimentation rates are known for different parts of the lake, for example, in radio dating technique or range line surveys, the average sedimentation rate for the lake can be obtained by:

$$R_s = \sum_{i=1}^{n} f_i R_{s_i}$$

where

R_s = average or mean rate of sedimentation (cm/yr);

f = weighing factor for area (area covered under different sedimentation rates);

R_{s_i} = rate of sedimentation of each area (cm/yr); and

i = number of sub-areas in which the lake bottom has been divided.

6.2.2 *Sediment Load and Stream Flow Discharge*

Annual sediment load is normally estimated from the annual sediment rating curve. The sediment rating curve expresses the relationship between the rates of sediment discharge to the corresponding flow discharge and it is usually presented graphically on a logarithmic scale. A sediment rating curve can be constructed from data obtained from incoming sediment load and stream flow discharge, usually measured at hydrometric gauging stations. The simplest method for obtaining an annual sediment rating curve is by adding all daily sediment loads and dividing the total by the number of days in the year for all years of available records. However, an alternative and a more practical method is based on estimating annual sediment loads using flow duration curves. An annual sediment rating curve can be constructed by simple regression of the annual average stream flow and annual average sediment loads. The annual rating curves at year *t* of suspended and bed load Q_t may be represented as:

$$\log_{10} Q_{sst} = a_1 + b_1 \log_{10} Q_t$$

$$\log_{10} Q_{sbt} = a_2 + b_2 \log_{10} Q_t$$

where

Q_{sst} = annual average suspended sediment load;

Q_{sbt} = annual average bed load; and

Q_t = annual average stream flow discharge.

a_1, b_1 and a_2, b_2 are rating curves coefficients for annual average suspended sediment and bed loads respectively. The total annual (average) sediment inflow in year *t* is then given as:

$$Q_s T_t = Q_{sst} + Q_{sbt}$$

where

$Q_s T_t$ = total annual (average) sediment inflow.

6.2.3 *Compaction of Deposited Sediment over Time*

The estimated average specific weight of the deposited sediment is used to convert the mass accumulated sediment in the lake into sedimentation volume. The accumulated lake sedimentation volume after *t* years can be estimated as:

$$LSV_t = \frac{LSL_t}{\text{Ɣ}t}$$

where

LSV_t = estimated accumulated lake sedimentation volume;

LSL_t = estimated accumulated weight of the lake sediment; and

$\text{Ɣ}t$ = specific weight of the deposited sediment at year *t.*

The estimation of the specific weight is particularly important in this process because any uncertainty in this value directly translates into the corresponding uncertainty in the volume of the estimated sediment deposit. The unit weight of sediment will increase each year the sediment deposit remains in the reservoir due to compaction through time by its own weight and the weight of water.

The most significant factors contributing towards the change of specific weight of deposited sediment are the size of the incoming sediment particles and the type or reservoir operation. Sediment deposition in a reservoir that is drawn down for considerable periods is subjected to exposure, consequently the sediment desiccates and become denser, thus increasing the unit weight. On the other hand, reservoir normally operating with a full pool would produce sediment with relatively lower unit weights. For a mixture of sediment, a weighted average of densities and consolidation constants must be used as follows:

$$\text{Ɣ}1 = 0.01\,[\text{Ɣ}1\,(c)Pc + \text{Ɣ}1\,(m)Pm + \text{Ɣ}1(s)Ps]$$

$$K = 0.01\,[K(c)Pc + K(m)Pm + K(s)Ps]$$

where

Ɣ1(*c*), Ɣ1(*m*) and Ɣ1(*s*) = initial specific weight of clay, silt and sand respectively;

K(*c*), *K*(*m*) and *K*(*s*) = consolidation constants for slay, silt and sand respectively; and

Pc, Pm and *Ps* = percentages of clay, silt and sand respectively.

Both Ɣ1 and *K* are functions of the type of lake operation and the size of sediment. The recommended values for Ɣ1 and *K* for clay, silt and sand are 416 and 256, 1 120 and 91 and 1 500 and 0 respectively.

6.3 Uncertainty in Lake Sedimentation Estimation

6.3.1 The following sections describe the possible sources of uncertainty and methods used for analyzing and quantifying the various uncertainties associated with lake sedimentation. The uncertainty of lake sedimentation estimation may arise from the variability of critical factors, called here the 'stochastic inputs' such as sediment inflow into the lake, stream discharge, lake operation and type of incoming sediment. These factors contribute to the uncertainty in the amount of lake sedimentation volume (LSV).

6.3.2 *Sources of Uncertainty in Parameters*

From the empirical models employed to estimate lake sedimentation above, factors affecting lake sedimentation may be attributed to the annual sediment inflows such as variation in the values of annual average suspended sediment load (Q_{sst}) and annual average bed load (Q_{sbt}). The uncertainty related to the type of incoming sediments can be represented as the various percentages of clay, silt and sand that is *Pc*, *Pm* and *Ps*, respectively. The different composition of incoming sediment would affect the estimated specific weight of the sediment, $\gamma 1$.

6.3.3 *Uncertainty Associated with Incoming Sediment*

Q_{ss} and Q_{sb} are inherently uncertain due to the nature of sedimentation process. Besides, their distributions are estimated from a limited sample of data. When data for Q_{ss} and Q_{sb} are not measured and need to be predicted from inflow, a generally adopted approach of sediment rating curve can be used. This approach, however, introduces extra uncertainties through the regression method. The particle size distribution of the bed load is used as the basis of estimating of the proportion of incoming bed load from the suspended data collected at the gauging station.

6.3.4 *Uncertainty Associated with Sediment Composition*

The sediment entering a lake is generally a mixture of clay, silt and sand. The fraction of each type of sediment namely, *Pc*, *Pm* and *Ps*, for clay, silt and sand respectively varies every year.

7 ESTIMATION OF EXPECTED LIFE OF LAKE

The computation of lake life provides an idea about the time period after which the lake will not be useful for water related activities. This may happen in two ways, that is, when the water of the lake is polluted up to an extent that it cannot be used for all practical purposes or the capacity of the lakes is reduced due to sedimentation up to an extent that it is not possible to meet out the water demand. This exercise should be done periodically to understand the lake environment and to plan the suitable measures timely for lake restoration, if the reduction of lake capacity is found at a higher rates or higher order of lake eutrophication is observed. The expected useful life of the lake is determined by dividing mean depth of the lake by weighted average rate of sedimentation. However, the validity of predicted lake life depends on the accuracy of mean depth of the lake. Although, the effect of compression of sediments by its weight is automatically included partly while estimating the rate of sedimentation, for an accurate estimate on the useful life of a lake, the effect of compression needs to be considered fully. Both ^{210}Pb and ^{137}Cs geochronological dating are powerful techniques for determining recent sediment accumulation rates in lakes and indirectly the useful life of them. The lake life is estimated taking into account the estimated sediment accumulation rates in the single zone and the present volume of the lake. The useful life of a natural lake is calculated as;

$$L = \frac{D_m \times 100}{R_s}$$

where

L = useful life of the lake, years;

D_m = mean depth of the lake, m; and

R_s = rate of sedimentation, cm/year.

Uncertainty in estimated life of the lake is calculated as:

$$\sigma_L^2 = L^2 \times 100^2 \times \left(\frac{\sigma_{D_m}^2}{D_m} + \frac{\sigma_{R_s}^2}{R_s^2}\right)$$

The mean depth, D_m is calculated as:

$$D_m = \frac{V}{A_s}$$

Uncertainty in estimated mean depth of the lake is calculated as:

$$\sigma_{D_m}^2 = D_m^2 \times \left(\frac{\sigma_v^2}{V^2} + \frac{\sigma_{A_s}^2}{{A_s}^2}\right)$$

where

D_m = mean depth of the lake, m;

V = lake volume, m^3; and

A_s = Average spread of the lake, m^2.

8 CONTROL OF LAKE SEDIMENTATION

The various sediment control methods in lakes can be divided into three categories:

a) Control of sediment generation in the lake catchments;
b) Control of sediment inflow to lakes; and
c) Sediment removal from lakes.

First category (a) consists of preventive measures while categories (b) and (c) are remedial measures. Preventive measures emphasize on reduction of sediment generation while controlling measures emphasize on reduction of sediment deposition in the water bodies.

8.1 Control of Sediment Generation in Lake Catchments

The primary objective of this method is to reduce generation of sediment within the lake catchment through control of soil erosion using soil conservation practices. Some of the important soil conservation practices are:

8.1.1 *Agronomic Practices*

a) Contour ploughing or contour farming;
b) Terracing or terrace farming;
c) Cover crops;
d) Special cropping methods:
    1) Crop rotation,
    2) Strip cropping,
    3) High density cropping,
    4) Growing crops that provide maximum cover,
    5) Mixed cropping, and
    6) Inter cropping.
e) Mulching;
f) Windbreaks; and
g) Soil management.

8.1.2 *Engineering Measures*

If the agronomic methods alone are not adequately effective, some mechanical measures, also called engineering measures may be needed to be adopted (one or more) to supplement them. These include:

a) Basin listing;
b) Sub-soiling;
c) Contour bunding;
d) Graded bunding or channel terrace; and
e) Bench terracing.

8.1.3 *Forestry Practices*

a) Rotational grazing; and
b) Afforestation and reforestation.

If the lake catchment is not very large, the effect of various soil conservation measures can be felt in short time. But if vast areas with poor natural conditions are involved, the soil conservation works can hardly be effective in a short period of time.

8.2 Control of Sediment Inflow to Lakes

If control of erosion in the lake catchment is not undertaken or fails to provide the requisite results, control of amount of sediment inflow to the lake is necessary. A large part of the finer particles can be prevented by the application of these techniques. These techniques include:

8.2.1 *Structural Measures*

In this method reduction of sediment inflow to lakes is achieved by constructing various types of structures in the catchment. Some of the structures are:

8.2.1.1 *Sediment basin*

A sediment basin is a temporary or permanent dam or basin or pond used to collect, trap and store sediment or as a flow detention facility for reducing peak runoff rates and thereby to settle out sediments. It is especially used to store sediment produced by construction activities.

a) A temporary sediment basin used in combination with other control measures, such as mulching, is known to be effective for removing sediments;
b) Sediment basin may not be practical in highly erodible soil types (0.01 inch and smaller soils, very fine sand, silt and clay) due to extremely large basin size requirements. In such cases, additional control measures such as filter cloth around the pond riser should be used to minimize release of fine silts;
c) If filter cloth is used, regular inspection and replacement is required to deal with clogging; and
d) A sediment basin should not be located in any active stream channel.

8.2.1.2 *Sediment trap*

A sediment trap is a temporary structure, basically an embankment built along a waterway or low-lying area, generally used on a construction site in the lake catchment, to capture eroded or disturbed soil that is washed off during rain storms.

a) They are typically installed at the perimeter of a site and above storm drain inlets;
b) They are commonly used on small construction sites, where a sediment basin is not practical;
c) They are installed before land disturbance (earth moving, grading) begins on a construction site; and
d) They are often used in conjunction with erosion controls and other sediment control practices.

8.2.1.3 *Check dams or gully plugs*

A check dam, also called gully plug, is a small, sometimes temporary dam, constructed across a swale, drainage ditch, or waterway to reduce water flow velocity by flattening the gradient of the channel. Although, check dams do not primarily function as sediment trapping devices, some sedimentation may result behind the dam.

a) They are generally used when other flow-control practices, such as lining the channel is impractical;
b) They are commonly used in degrading temporary channels, in which permanent stabilization is impractical and infeasible, in terms of resource allocation and funding due to the short life period;
c) They are used when construction delays and weather conditions prevent timely installation of other erosion control practices;
d) They serve as temporary grade-control mechanisms along waterways until resolute stabilization is established or along permanent swales that need protection prior to installation of a non-erodible lining;
e) They remove coarse and medium size sediment from runoff. However, most fine silt and clay particles will pass over or through the voids on these structures;
f) Primarily, check dams diminish loads flowing out of the gully mouth. They raise the gully channels and flatten the gully bottom so that various types of erosion are weakened and checked;
g) The size and shape of a drainage area, as well as the length and gradient of its slopes, have an effect on the run-off rate and amount of surface water. Therefore, all topographic characteristics should be studied in detail before gully-plugging work begins. There are several designs for how check dams should be constructed;
h) The kind of gully plug that should be constructed depends on the local situation (what kind of material is available, slope gradient, is it a permanent solution, what tasks are intended);
j) In general, woven-wire, brushwood, logs, loose stone and boulder are used in check dams to facilitate the growth of permanent vegetative cover; and
k) Check dams are typically, though not always, implemented as a system of several check dams situated at regular intervals across the area of interest. In a series of check dams, the top centre of the downstream check dam should be at the same elevation as that of the bottom of the upstream check dam.

The spacing between the two check dams can be calculated by multiplying the height of the check dam by the slope factor H : V or by dividing by the slope percentage.

Check dams require periodic repair and maintenance. Maintenance of check dams involves:

a) Inspection of check dams and drainage ways for damage after each runoff event, correct all damages immediately;
b) If significant erosion occurs between dams, additional protection may be required. This may include protective riprap liner in that portion of the channel or placing additional check dams;
c) Remove sediment accumulated behind the dams to prevent damage to channel vegetation; and
d) Add rock or remove rock as needed to maintain design height, cross section, and flow-through characteristics.

8.2.2 *Vegetative Screen*

This is a very effective method wherein vegetative screens are located immediately upstream of the lake to trap and prevent sediment from entering the lake. However, its disadvantages are that sediment deposited leads to progressive deposition of delta and increased vegetation is likely to increase the water consumption. The effectiveness of the method depends on the vegetation type and the length of the vegetation filter strip. While vegetation type affects the run-off reduction, the length of vegetation filter strip affects the sediment trapping performance.

8.2.3 *Bypassing of Heavily Sediment-Laden Flows*

This method involves construction of bypassing channels or conduits to bypass large part of the flow, before they enter the lake, when a great amount of sediment is carried by inflowing river/stream, particularly during flood periods.

8.2.4 *Measures within the Water Body to Control Sediment Inflow*

Besides the above structural measures which are undertaken outside the lake or within the catchments, certain measures are undertaken within the water body itself. These are:

8.2.4.1 *Revetments*

Revetments are used as stabilization structures to line the lake banks to absorb the energy of water and prevent erosion and subsequent sediment deposition in lakes. The materials used for this purpose include wooden piles, loose-piled boulders or concrete for more solid banks.

a) Revetments are always made as sloping structures. Normally, 1 : 2 slope is used in revetments;

b) Very often constructed as permeable structures to enhance wave energy absorption and minimizing reflection and wave run-up;

c) Can also consist of different kinds of concrete slabs, some of them are permeable and have interlocking, to increase their functionality in terms of absorption and strength;

d) Should not be used at locations, where the lake shore is used for recreation or fishing activities due to unsuitability of such slopes for the purpose;

e) If revetment is required on lake banks used for recreational use or for the landing or hauling of small fishing boats, a more gently sloping structure with a smooth surface is recommended;

f) If revetments consist of sand-filled geotextile fabric bags, mattresses and tubes, they must be protected against UV-light to avoid weathering of the fabric as the fabric is fragile against mechanical impact; and

g) As far as possible, sand-bagging be used only as emergency protection as their appearance is not natural.

8.2.4.2 *Turbidity curtains*

A turbidity curtain, also called ‘turbidity barrier’ or ‘silt curtain’, is a flexible, impermeable barrier used to trap sediment in water bodies.

a) A turbidity curtain is generally used when construction activity occurs within a water body or along its shoreline and is of short duration, generally less than one month;

b) They are meant for use in calm water surfaces;

c) This curtain is generally weighted at the bottom to ensure that sediment does not travel under the curtain.

d) They work on the principle of settlement of suspended matter;

e) They can fail when subjected to significant water flows or wave action;

f) They cannot be used as a filter across the inflowing stream flow;

g) They should be oriented parallel to the direction of flow;

h) There is also some possible mobilization of fine sized settled particles after removal;

j) For lakes/lake shores not subject to heavy wave action, the curtain height shall provide sufficient slack to allow the top of the curtain to rise to the maximum expected high-water level (including waves) while the bottom maintains continuous contact with the bottom of the water body;

k) For lakes/lake shores subject to heavy wave action, the curtain height should provide sufficient slack to allow the top of the curtain to rise to the maximum expected high-water level (including waves) while the bottom remains one foot above the bottom, so that the curtain does not stir up sediment by repeatedly striking the bottom;

m) The curtain should be constructed of nonwoven material of bright colours, so as to attract the attention of boaters or swimmers using areas near the curtain site;

n) The various material used for fabrication of turbidity curtain include rope or cable with floats, pre-manufactured turbidity barrier (which generally consists of a woven geotextile with a polymer coat); and

p) The turbidity curtain need to be inspected daily and repaired or replaced immediately, if so required.

8.3 Sediment Removal

This method is used if prevention of sediment flow does not yield desirable results. Two important methods in this category are:

8.3.1 *Lake Drawdown Followed by Bulldozer and Scraper Excavation*

This method needs that water must be pumped or drained from the lake sufficiently so that earth moving equipment can be operated successfully. It is generally suitable only for small lakes.

8.3.2 *Dredging*

Although commonly used as a synonym, desilting means the removal of silt from the lake while dredging refers to the technique employed for the purpose. The information on sediment deposit zones in lakes, if available, can be used for determining the areas of desilting of the lake. Depth of dredging depends upon the purpose of dredging. Dredging is considered as the most effective of all the sediment control methods. Modern dredging equipment are reasonably efficient at removing large volumes of sediment. lake filled with sediments and not suitable for boating, swimming, fishing etc, dredging can be only option to restore the lake. Size of the lake does not pose any constraint for dredging. However, cost benefit ratio and lifespan of benefits is likely to be more for large lakes with small catchment than for small lakes with large catchments.

Since total cost of dredging project is generally calculated on the basis of sediment removal, it is necessary to estimate the amount and type of sediment contained in the lake basin using the hydrographic data.

8.3.2.1 *Types of Dredgers*

a) Mechanical dredgers — Most common are grab type dredgers. They must discharge in the immediate vicinity of the sediment removal area. They are normally limited to a reach of not more than 30 m to 40 m. They create uneven bottom and turbid water conditions. Turbidity curtains may be used to overcome the turbidity problem.

b) Hydraulic dredgers — Several types of hydraulic dredgers are in use such as suction dredge, hopper, dustpan and the cutter head suction dredge. Their suitability varies as per use. For example, hopper dredges are impractical for small inland lakes. Cutter head suction dredge is most popular for use in inland lakes.

   Hydraulic dredgers are not confined in operation by limitation of cable reaches like the mechanical dredgers. They can be operated continuously. However, slurry removed by these dredgers contains only about 20 percent solids and rest is water which means that they require large disposal areas.

c) Special purpose dredgers — They are used for removal of very fine sediments or contaminated sediment from lakes that have soft and, viscous sediments. They operate on the principle that sediment and water, under hydrostatic pressure, will be forced into pump body which is maintained at atmospheric pressure. Filling efficiency, therefore, increases with depth as hydrostatic pressure increases. However, at depth less than 10 m hydrostatics pressure is insufficient to operate the system.

8.3.2.2 *Disadvantages of dredging*

a) Costly;
b) Can cause adverse impacts on aquatic ecosystems;
c) Dredge spoils may contain toxic chemicals that may have an adverse effect on the disposal area;
d) Dredging often dislodges chemicals residing in benthic substrates and injects them into the water column;
e) Short term increases in turbidity due to resuspension of bottom sediment, which can affect aquatic species metabolism and interfere with spawning; and
f) Problem of disposal of the dredged material.

8.3.2.3 *Selection of dredge*

Selection of dredge depends on several variables like availability, project time constraints, slurry transport distances, discharge head, and physical and chemical characteristics of the dredged material**.**

8.3.2.4 *Disposal of sediment*

The major problems associated with the disposal of dredged material are:

a) Ensuring the availability of a sufficient disposal area for initial and future maintenance dredging within a reasonable (economically feasible) distance of the dredging operations; and
b) Potential adverse environmental effects associated with the disposal of dredged material, including an increase in turbidity, the resuspension of contaminated sediment and a decrease in dissolved oxygen.

Primary factor controlling the design of disposal area is the amount of dredged material that must be contained. Since there are lot of suspended sediments in the slurry, factors such as sediment grain size, specific gravity, plasticity and settling characteristics of the dredged material must also be considered in the design.

ANNEX A

(*Foreword*)

COMMITTEE COMPOSITION

Reservoirs and Lakes Sectional Committee, WRD 10

Organization	*Representative(s)*
National Institute of Hydrology, Roorkee	Dr Sudhir Kumar Director **(*Chairperson*)**
Bhakra Beas Management Board, Chandigarh	Er Hushan Lal Kamboj
Central Water and Power Research Station, Pune	Dr Neena Isaac Shri Srishailam (*Alternate* I) Dr V. M. Prabhakar (*Alternate* II)
Central Water Commission, New Delhi	Shri Goverdhan Prasad Shri S. S. Bonal (*Alternate*)
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Department of Water Resources, Government of Odisha	Chief Engineer (D & R) Director (Head Works) (*Alternate*)
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J&K Lakes and Water Way Development Authority, Srinagar	Executive Engineer
Maharashtra Engineering Research Institute, Nashik	Shri Yashavant Rao Bhadane
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National Water Development Agency, New Delhi	Shri R. K. Jain Shri S. C. Awasthi (*Alternate*)
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Sardar Sarovar Narmada Nigam Limited, Gandhinagar	Shri C. V. Nadpara Shri R. G. Kanoongo (*Alternate*)
Satluj Jal Vidyut Nigam Limited, Shimla	Shri Vinay Guleria Shrimati Sudha Devi (*Alternate*)
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